

SIBERIAN PINE DECLINE AND MORTALITY IN SOUTHERN SIBERIAN MOUNTAINS

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Abstract

The causes and resulting spatial patterns of Siberian pine mortality in eastern Kuznetzky Alatau Mountains, Siberia were analyzed based on satellite (Landsat, MODIS) and dendrochronology data. Climate variables studied included temperature, precipitation and Standardized Precipitation-Evapotranspiration Index (SPEI) drought index. Landsat data analysis showed that stand mortality was first detected in the year 2006 at an elevation of 650 m, and extended up to 900 m by the year 2012. Mortality was accompanied by a decrease in MODIS-derived vegetation index (EVI).. The area of dead stands and the upper mortality line were correlated with increased drought. The uphill margin of mortality was limited by elevational precipitation gradients. Dead stands (i.e., >75% tree mortality) were located mainly on southern slopes. With respect to slope, mortality was observed within a 7°-20° range with greatest mortality occurring on convex terrain. Tree radial increment measurements correlate and were synchronous with SPEI ($r^2=0.37$, $r_s=80$). Increasing synchrony between tree ring growth and SPEI indicates that drought has reduced the ecological niche of Siberian pine. The results also showed the primary role of drought stress on Siberian pine mortality. A secondary role may be played by bark beetles and root fungi attacks.

The observed Siberian pine mortality is part of a broader phenomenon of “dark needle conifers” (DNC, i.e., Siberian pine, fir and spruce) decline and mortality in European Russia, Siberia, and the Russian Far East. All locations of DNC decline coincided with areas of observed drought increase. The results obtained are one of the first observations of drought-induced decline and mortality of DNC at the southern border of boreal forests. Meanwhile if model projections of increased aridity are correct DNC, within the southern part of its range may be replaced by drought-resistant *Pinus silvestris* and *Larix sibirica*.

Keywords: climate-induced tree mortality, drought impact on forests, tree die-off, Siberian pine decline

36

37 **1. Introduction**

38

39 Forest decline and mortality caused by drought during the last decades has been documented
 40 on every continent (Allen et al., 2009). Elevated temperatures and water stress has caused forest
 41 mortality in Europe, including increased stand mortality in Spain (Penuelas et al., 2001), France
 42 (Breda et al., 2006; Landmann and Dreyer, 2006), Switzerland and Italy (Bigler et al., 2006;
 43 Dobbertin and Rigling, 2006). In North America *Populus tremuloides* mortality was observed
 44 across a million hectares (Hogg et al., 2008; Worrall et al., 2010; Anderegg et al., 2012). In the
 45 south-western part of USA drought-induced mortality of *Pinus edulis* was also documented for
 46 an area of over a million hectares (Breshears et al., 2005; Raffa et al., 2008; Van Mantgem et al.,
 47 2009). In Russia birch (*Betula pendula*) stands decline was recently described in the southeastern
 48 Siberia forest-steppe (Kharuk et al., 2013).

49 Scenarios of climate changes are likely to include further increases in drying, frequency and
 50 severity of droughts in some forested areas (Christensen et al., 2007; IPCC, 2007; Seager et al.,
 51 2007; Sterl et al., 2008; Aitken et al., 2008). This may lead to reduced forests growth and
 52 increases in stress and mortality caused by synergy of drought impact and climate-induced
 53 changes in the dynamics of dendrophyl insects and fungi (Lucht et al., 2006; Scholze et al.,
 54 2006; Lloyd and Bunn, 2007). Severe water stress is decreasing both growth and oleoresin
 55 production, making trees more susceptible to bark beetle attack. In addition to water stress
 56 affecting host tree susceptibility, insect population dynamics were directly affected by increasing
 57 temperature (Hansen et al., 2001; Breshears et al., 2005).

58 In Russia decline and mortality of “dark needle conifers” (DNC: spruce (*Picea obovata*),
 59 Siberian pine (*Pinus sibirica*), fir (*Abies sibirica*)) were reported from the western border (i.e.,
 60 Kaliningrad region) to the Russian Far East. During the 21st century, climate-caused mortality
 61 was described in official Russian reports as the third-ranked factor (following fire and pest
 62 impacts) (Efremov et al., 2012). In Archangelsk in the European part of Russia spruce decline
 63 was observed over an area >1.6 million ha with mortality on the territory >390 thousands ha
 64 (Fig. 1 (site 1)). Other potential causes of forest mortality considered were over mature stands,
 65 drought, root fungi and insect attacks (Chuprova, 2008; Sanitary, 2008). In the Russian Far East,
 66 mortality was reported over the vast area of mixed spruce (*Picea ajansis*) and fir (*Abies*
 67 *nephrolepis*) forests within the Sihote-Alin Ridge (Fig.1 (site 7)). Mortality was observed mainly
 68 for the mature stands (Age =100-160 years), whereas regeneration was usually not damaged.
 69 Decline and die-off of spruce-fir stands were considered to be caused by “unfavorable climatic
 70 factors with fungi as a co-factor” (Man’ko et al., 1998). According to the Russian Forest Service,

Siberian pine and fir decline and mortality were observed in the southern Siberian Mountains (Kuznetzky Alatau and Sayan Mountains) and in the Baikal Mountains (mixed fir and Siberian pine stands) (Fig. 1 (Sites 2, 3, 4, 5)). In addition, birch mortality was documented in the Trans-Baikal area (Kharuk et al., 2013 (Fig. 1 (site 6))).

The goal of this paper was spatial and temporal analysis of Siberian pine mortality within the Kuznetzky Alatau Mountains, and analysis of potential causes of this phenomenon. We considered the following hypotheses. 1. Siberian pine decline and mortality were caused by drought. 2. Mortality pattern was dependent on relief features. The following questions were also addressed: When did the Siberian pine decline and mortality begin? What were the causes of stand mortality? What are the spatial and temporal patterns of mortality?

2. Material and methods

2.1. Study area

The study area (designated as the “Black Iyus” (BI) site) was located within the Kuznetzky Alatau Mountains (Fig. 1). These mountains are part of the Sayan-Altai Mountains in southern Siberia and composed of several northward oriented ridges with length and width about 300 km and 150 km, respectively, and maximal height about 2200 m. These mountains have relatively gentle slopes and are composed of limestone, quartzite, argillaceous and siliceous slates, with multiple intrusions of granites, diorite, gabbro and tuff.

2.2. Climate

Monthly climate data for the area were obtained from KNMI Climate Explorer (Climate Explorer, <http://climexp.knmi.nl>). Data were averaged for a cell size $0.5^{\circ} \times 0.5^{\circ}$. Climate within the study area is continental with cold long winters and warm or hot summers. On western facing slopes annual precipitation is about 600-800 mm (with >1500 mm) within the central windward part of mountains). The western facing slopes actually create a "rain shadow" effect that results in a decrease in precipitation on the eastern slopes, where annual precipitation were in the range of 400-500 mm. Winter winds (predominately from the south-west) resulted in greatest accumulation of snow on northern and eastern slopes. Climate data for the BI site are presented in Table 1 and Fig. 2 (the beginning of the record is considered to be the year 1940 when reliable meteorological observations started). According to this record, mean January and July temperatures are -21.4°C and $+16^{\circ}\text{C}$, respectively.

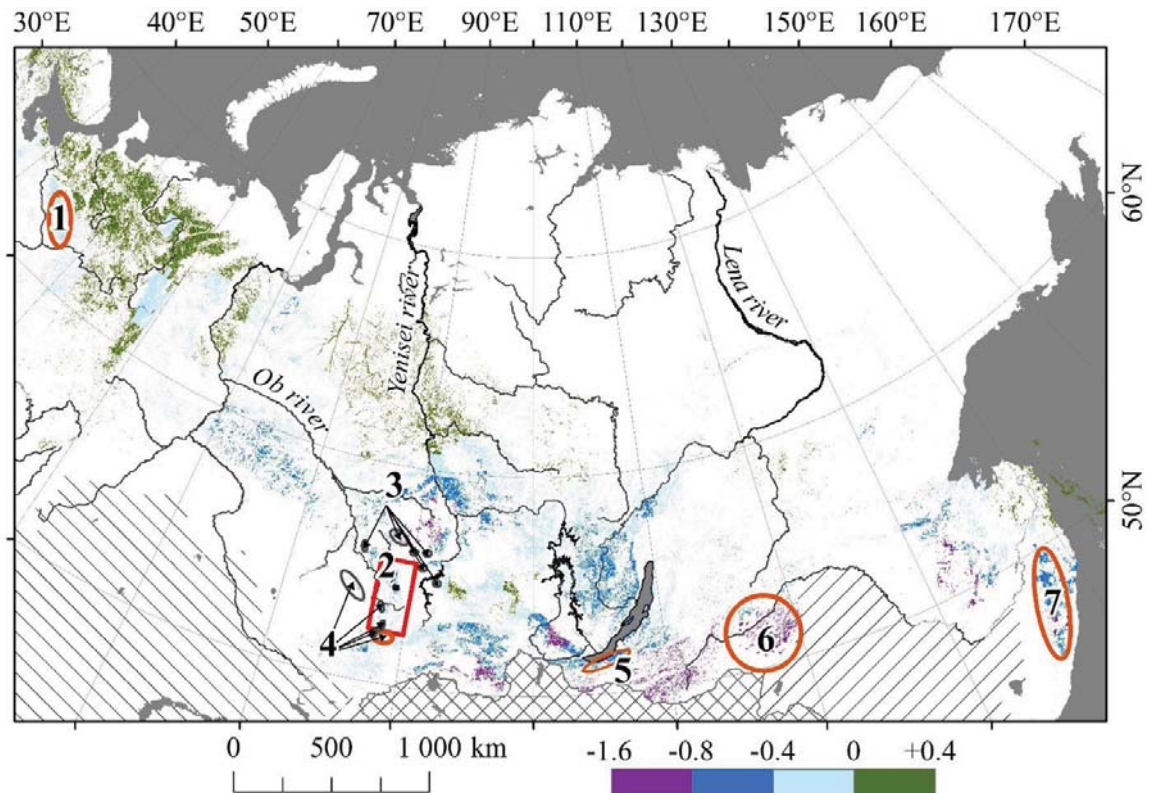


Fig. 1. Location of forest stands decline and mortality in Siberia. Background: evergreen conifer map (Bartalev et al., 2011). Color scale: SPEI (Standard Precipitation Evaporation Index) anomaly (2000-2009 vs 1902-2009 yr.). Sites: 1 – spruce stands in Archangelsk region; 2 – DNC of Kuznetzky Alatau Mountains; 3, 4 – DNC stands in southern Siberia; 5 – fir and Siberian pine site in southern Baikal area; 6 – birch stands within Trans-Baikal area (Kharuk et al, 2013); (7) – spruce stands in Russian Far East (Man’ko et al, 1998).

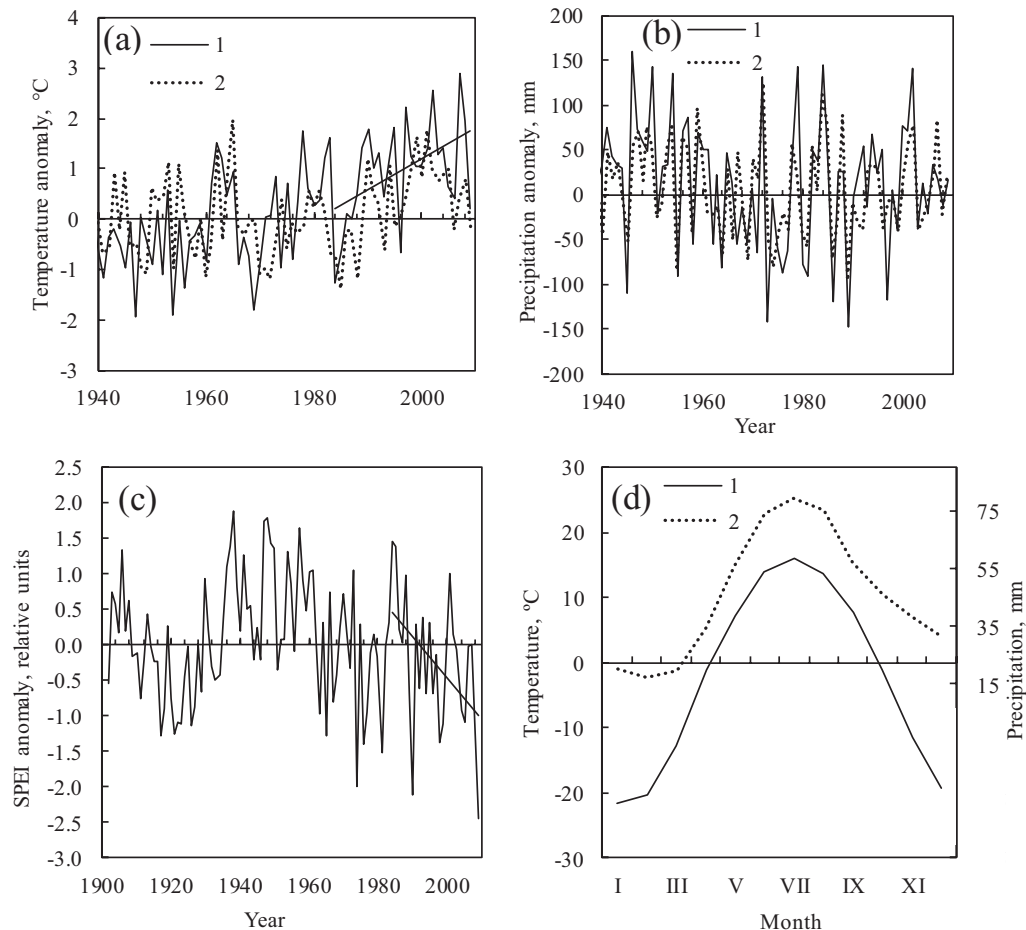
Table 1. Climate data for the “Black Iyus” site.

Variable (1940-2009 yr)	Ann ual	Jun- Aug	Dec- Feb
Mean temperature, °C	-2.2	14.5	-20.0
Mean sum of precipitation, mm	562	234	71

2.3. Vegetation

In Kuznetzky Mountains, tundra communities are typical at high elevations (1350-1500 m.a.s.l.) with mountain-tundra soils. Within the subalpine belt (1100-1350 m) alpine meadows and sparse vegetation (*Betula tortuosa*, *Larix sibirica*, *Pinus sibirica* and *Abies sibirica*) grow on

121 mountain-subalpine soils. Top and middle parts of the forest belt (600-1100 m) are composed of
 122 Siberian pine dominated stands with an admixture of fir and spruce (*Picea obovata*). Soils are
 123 mountain light-grey rocky podzolized. Low elevations are occupied by larch and pine (*Pinus*
 124 *silvestris*) stands with admixture of Siberian pine and birch (*Betula pendula*). Here soils are
 125 mountain rocky podzolized. Steppes are found on steep south facing slopes at the lowest
 126 elevations (500-600 m.a.s.l.)



127
 128 Fig. 2. Climate variables within “Black Iyus” site. (a), (b) - mean air temperature and
 129 precipitation anomalies, correspondingly (1 – annual, 2 - May-August data); (c) – anomaly of
 130 SPEI drought index; (d) – annual (1) temperature and (2) precipitation. Trends for annual
 131 temperature (a) and SPIE (c) were significant at $p < 0.05$.

133 2.4. Field studies

134
 135 Forest mortality within the BI site was reported by local foresters in the year 2006. Field studies
 136 were executed in the summer of 2012 and included forest type description, trees height and
 137 diameter measurements, canopy closure estimation, and cutting of tree disks for

dendrochronology analysis. The BI site is located within an area with elevations of about 640-1040 m a.s.l. Stands are formed by Siberian pine (>95% of trees) with admixture of *Abies sibirica* and *Picea obovata*. Canopy closure was about 0.8-0.9. Average tree height was about 30 m, and DBH was 28 cm. Stands were mature (mean age of trees was about 160 years; the maximum Siberian pine lifetime is about 600-800 years). Ground cover was mesophytic (sedges dominant). Litter thickness was about 3-5 cm. Soils were light-gray forest type underlined by stony clay at 10-15 cm deepness. There were no signs of fires within study area, i.e., there were no carbon and burnmarks on the boles. During the year of ground measurements logging was carried out within areas of stands dieback and mortality. It is necessary to note that according to Russian forest rules logging of Siberian pine stands is strictly prohibited except in decline or dead stands. The area of logging within BI site is about 15 ha. Discs for dendrochronology analysis were collected at about breast height.

2.5. Dendrochronology analysis

The dendrochronology dataset included 56 disks (24 from living trees, 11 from declining and 21 from dead trees). The surface of each disk was sanded, planed with a scalpel and treated with a contrast enhancing powder. The widths of tree rings were measured with 0.01 mm precision using a linear table instrument (LINTAB-III). The TSAP and COFECHA computer programs were used in tree ring analysis and cross dating of chronology (Holmes, 1983; Rinn, 1996). Dates of tree mortality were determined based on the master-chronology method (Fritts, 1991). An initial master chronology was constructed based on 10 living trees. This master-chronology was used for cross dating of the remaining samples. As soon as a given sample was dated, it was included into the master chronology. This procedure provided increased reliability of further analysis. The final master chronology included 39 individual tree-ring series. The mean coefficient of correlation between individual tree-ring series and master-chronology was 0.43. The mean sensitivity of individual series included into master-chronology was 0.173. Discs with missing rings ($n = 8$) were not included into the master-chronology, but were involved in further analysis. Discs which were not possible to cross-date ($n = 9$) were removed from further analysis. Thus the final dataset ($n = 47$) was divided into “survivors” ($n = 15$) and “dead and declining” ($n = 32$) groups. This division was based on radial increment trends during the last decade (2000-2011) as described.

Trees with positive tree ring increments formed a “survivors group”, whereas a second group contained trees with negative increment trend and dead trees. For both groups standard and residual chronologies were constructed. Standard chronologies were indexed using ARSTAN

software (i.e., double detrending to remove long-term trends by negative exponential curve and a linear regression; Cook and Holmes, 1986). The resulting chronologies were a unitless index of radial tree growth. The residual chronologies were constructed based on standard chronologies by elimination of autocorrelation, i.e., increasing a climate signal (Cook and Holmes, 1986). Statistical analysis was carried out using Excel and StatSoft software; Student's *t*-test was used to estimate result significance (StatSoft Inc, 2013). In addition to the correlation coefficient (*r*), the coefficient of synchronization (*r_s*) was determined. The latter was calculated as the ratio of the number of annual segments with the same direction (i.e., increasing or decreasing growth increment) to the total segment number (Shiyatov, 1986).

2.6. Satellite data

2.6.1. Aqua/MODIS and Terra/MODIS data analysis

Aqua/MODIS and Terra/MODIS satellite data were used for temporal analysis of stands vigor based on Enhanced Vegetation Index (EVI). EVI is responsive to canopy structural variations, including leaf area index, stands vigor, canopy type, plant physiognomy, and canopy architecture (Huete et al., 1999). Technically EVI data are available as a ready to use MODIS product MOD13Q1 from NASA's site (EOSDIS, <http://reverb.echo.nasa.gov>). For this purpose a temporal series of satellite data from MODIS products were compiled.

EVI is defined as:

$$EVI = G \times (\rho_{NIR} - \rho_{red}) \times (\rho_{NIR} - C_1 \times \rho_{red} + C_2 \times \rho_{blue} + L)^{-1}$$

where ρ_{NIR} , ρ_{red} and ρ_{blue} are atmospherically-corrected surface reflectance in MODIS bands #1 (620-670 nm), #2 (841-876 nm) and #3 (459-479 nm); *L* is the canopy background adjustment; *C₁* and *C₂* are the coefficients of the aerosol correction; *G* – gain factor (Huete et al., 1999).

In this study the MODIS EVI values covered the period from 2000 to 2012 with ground resolution of 250×250 m. Earlier it was reported that Terra/MODIS sensor degradation impacted NDVI trend analysis (Wang et al., 2012). Here Terra/MODIS data were used for the 2000-2001 period only, when there was no significant sensor degradation. The time interval 2002-2012 was analyzed based on Aqua/MODIS data which were already corrected (Wang et al., 2012).

A mask of evergreen conifers for the whole of Siberia and the study area in particular was generated based on the Terra Norte forest vegetation map (Bartalev et al., 2011). This mask was used to track changes within evergreen conifer stands only.

2.6.2. Landsat data and GIS analysis

Landsat scenes (MSS/TM/ETM+, 15-60 m spatial resolution, acquired during the years 1976-2012) were obtained from USGS GloVis (<http://glovis.usgs.gov>). The selected scenes were georeferenced to topographic maps (scale 1:100000). Dead stands (i.e., those exhibiting >75% tree mortality) were visually detectable on the images. The total area of the analyzed territory was 382 ha. An analysis of the scenes showed that stand mortality could be detected as early as the year 2006. Also available were digitized maps of dead stands produced by a forestry expert for each year from 2006 to 2012. Image interpretation was facilitated by data acquired from our field studies. Polygons were delineated on an image display and recorded by ArcGIS software (<http://www.esri.com>).

Topography analysis of stand mortality was based on the DLR SRTM-X DEM product (<http://eoweb.dlr.de:8080/index.html>). DEM horizontal accuracy was ± 20 m (absolute) and ± 15 m (relative). The vertical accuracy was ± 16 m (absolute) and ± 6 m (relative). The minimum interval (contour) of elevation of 50 m was used. The following parameters were considered: elevation, aspect, slope steepness, and curvature (i.e., convex/concave slope parameters). Aspect, slope steepness and curvature data were calculated from SRTM-X DEM using ArcGIS tools. The aspect data were quantized into eight directions (i.e., by 45 degrees corresponding to north, northeast, east etc.). The distribution of landscape elements with given altitude, azimuth and slope steepness was uneven within the analyzed area and thus could lead to biased analysis. To avoid this, the data were normalized by the following procedure. The analyzed study area (about 400 ha) with given azimuth, slope steepness and elevation was related to the larger (“reference”) territory (ca 3000 ha) with similar parameters:

$$\kappa_{c(i)} = A_{c(i)-f} / A_{c(i)-I} \quad (1)$$

where the $c(i)$ subscript represents the i^{th} category of landscape feature c , $A_{c(i)-f}$ is the area of the given on-ground class within the i^{th} category of the topography feature c , and $A_{c(i)-I}$ is the area of the i^{th} category of topography feature c over the “reference” territory. ERDAS Imagine software (<http://geospatial.intergraph.com>) was used in the analysis.

2.7. Water balance estimation

For water balance estimation, the Standardized Precipitation-Evapotranspiration index (SPEI; Vicente-Serrano et al., 2010) was used. Like the PDSI (The Palmer Drought Severity Index;

Palmer, 1965), the SPEI measures drought severity according to intensity and duration, and can be used to identify the onset and end of drought episodes. The SPEI uses the monthly difference (D_i) between precipitation and PET (potential evapotranspiration):

$$D_i = P_i - PET_i$$

PET (mm) is obtained by:

$$PET = 16 \times K \times (10 \times T \times I^{-1})^m,$$

where T is the monthly mean temperature in °C; I is a heat index, which is calculated as the sum of 12 monthly index values, m is a coefficient depending on I , and K is a correction coefficient computed as a function of the latitude and month which takes into account number of sun hours in a day. SPEI data for the study area were calculated for the May-August period. May was added to summer period because May droughts were typical for the study area. Spatial resolution for the SPEI data was $0.5^\circ \times 0.5^\circ$ ($\sim 33 \times 56 \text{ km}^2$).

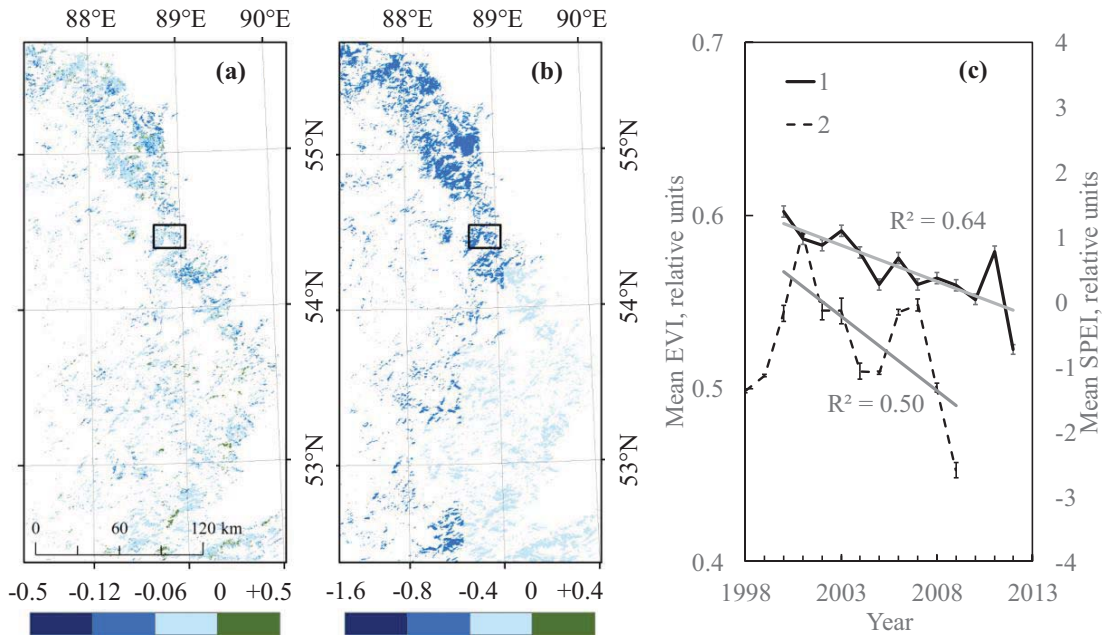
3. Results

3.1. Remotely sensed data

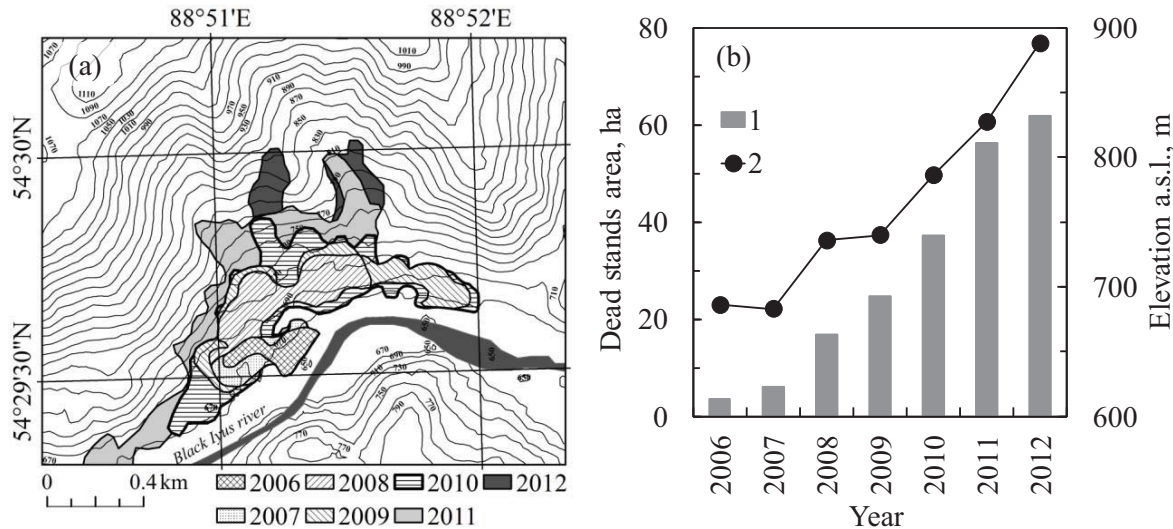
An overall decrease in Vegetation index (EVI) for “dark needle conifers” stands was observed within the Kuznetzky Alatau Mountains. This decrease in “greenness” was correlated with drought during the first decade of the 21st century (Fig. 3a, b). Within the BI site EVI decreased about ~4% ($p < 0.05$) between 2006 and 2012, and was accompanied with a drought increase (Fig. 3c). The dynamics of forest mortality are presented on Fig. 4, 5. With an increase in drought (i.e., SPEI decrease) the dead stands area increased ($r_1^2 = -0.98$) and stand mortality was propagated along the elevation gradient ($r_2^2 = -0.92$) (Fig. 5).

3.2. Relief features

Maximum mortality was observed on the slopes of southern and southeastern exposures (Fig. 6b). The location of dead stands was relatively higher within convex terrain elements (Fig. 5c). With respect to slope, mortality was maximal within the range of slopes between 7° and 20° (> 75% mortality; Fig. 6c). With respect to elevation, mortality was observed mainly within the lower elevation belt (starting from Black Iyus river level: 650 m a.s.l.) and decreasing upwards. No mortality was detected above 900 m (Fig. 6d). The elevational limit of tree mortality was negatively correlated with SPEI (Fig. 5).



272
273 Fig. 3. EVI and SPIE anomaly for the Kuznetsky Alatau Mountains and BI site. Box indicated BI location. (a) –
274 EVI anomaly (2012 vs 2000-2012 mean), (b) –SPIE anomaly (2000-2009 mean vs 1902-2009 mean), (c) – SPIE (1)
275 and EVI (2) dynamics for the BI site. Bars showed 0.95 confidence level. Trend are significant at $p < 0.007$ (EVI) and
276 at $p < 0.023$ (SPIE).



277
278 Fig. 4. (a) forest mortality map (background: a topo map) and (b) forest mortality dynamic (1 - dead stands area,
279 2 - elevation limit of dead stands at given year).

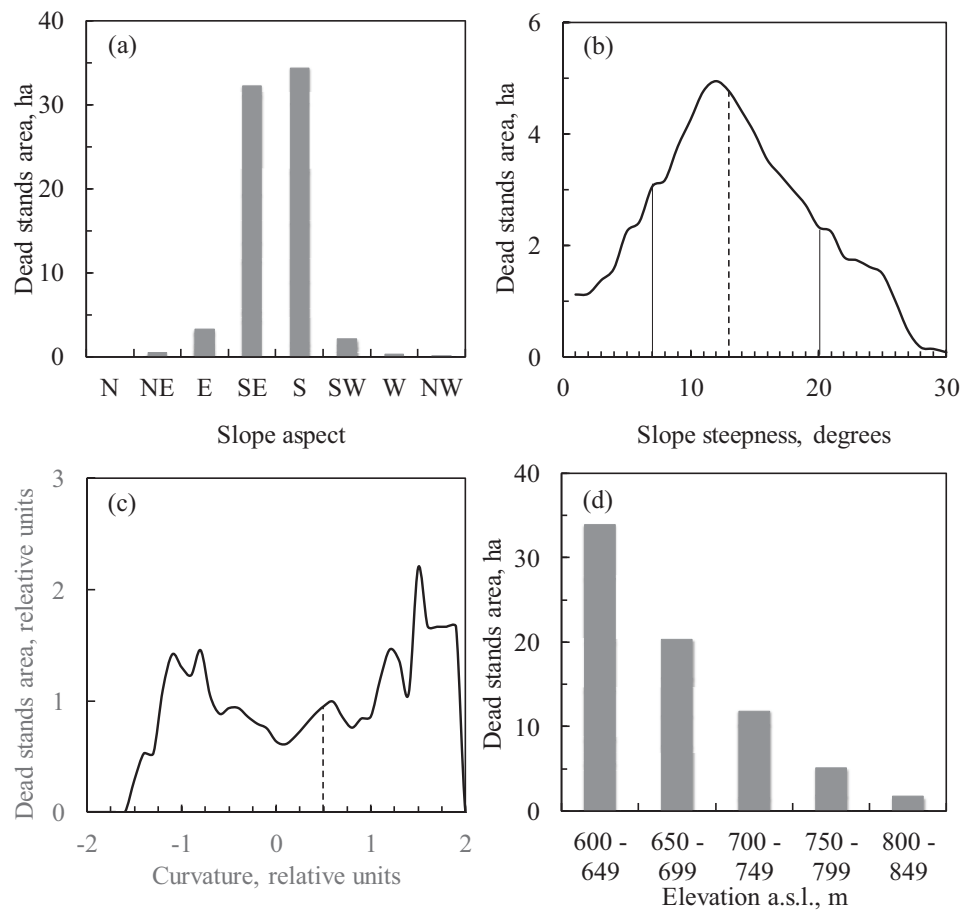
280 3.3. Dendrochronology data

281 The statistics of master-chronologies (both standard and residual) for “surviving” and “dead
282 and decline” groups are shown in Table 2. The mean tree ages of “survivors” and “dead and
283 decline” groups were 154 and 173 years, respectively. All groups have relatively high
284 correlations between individual series and master-chronology ($r^2 = 0.39-0.41$). Mean sensitivity
285 values which signify the relative change in ring-width from one year to the next, were low for all

286 Table 2. The tree-ring chronologies statistics

	Tree group		Master Chronology
	“Survivors”	“Dead & decline”	
Mean ring width (mm)	0.94	0.84	0.95
Maximum ring width (mm)	3.88	5.12	4.86
Mean sensitivity	0.180	0.183	0.173
Interseries correlation	0.39	0.41	0.43
Autocorrelation	0.69	0.63	0.60

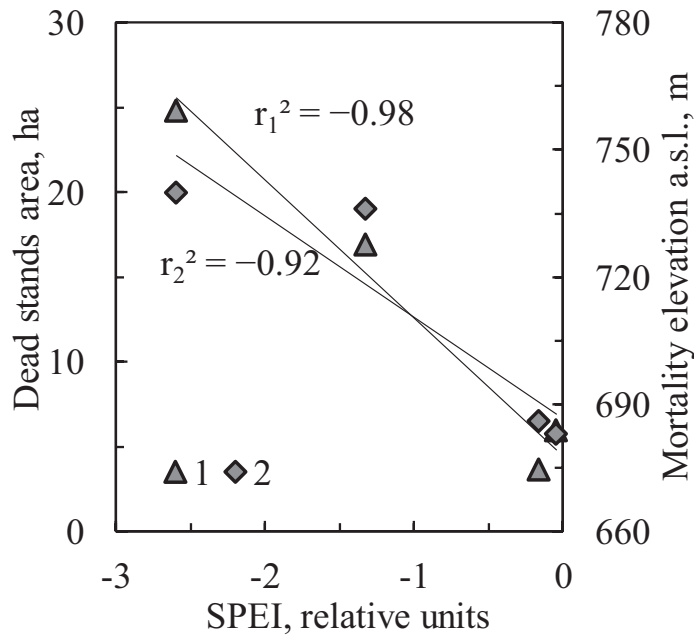
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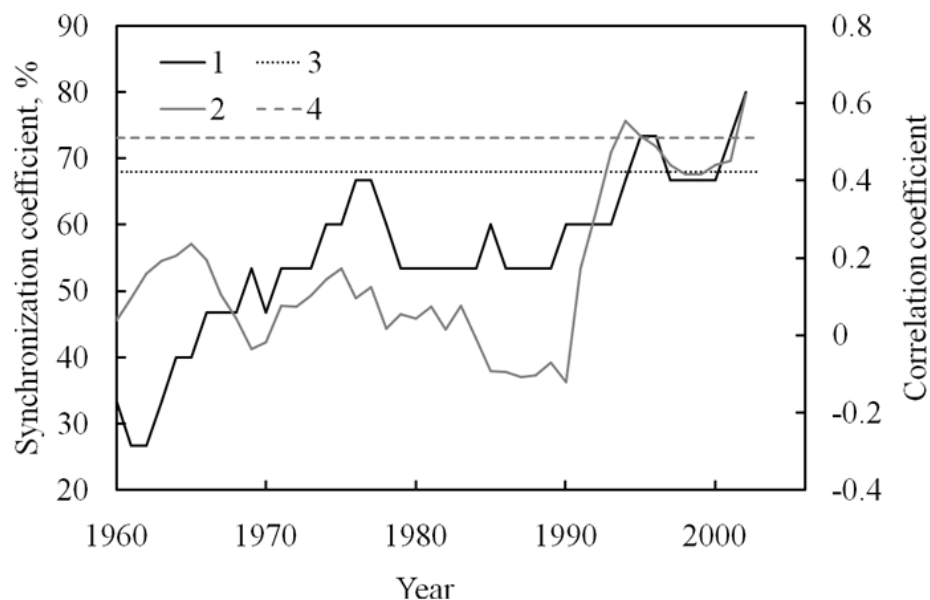
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289 Fig. 5. Dynamics of forest mortality with respect to relief features. (a) - mortality dependence on aspect, (b) -
 290 mortality distribution with respect to slope steepness (dashed line: a median, thin lines: boundaries of 75% of dead
 291 stands area), (c) – mortality distribution on concave/convex relief features, (d) - mortality dependence on elevation.
 292 groups (0.180-0.183; i.e., the climate signal was low), which is indicative for trees with a
 293 favorable growth pattern (Shiyatov, 1986). Correlations for “survived” and “dead and decline”
 294 chronologies with master-chronology (0.92-0.97) were very high, i.e., trees growth pattern was
 295 homogeneous (Fritts, 1991).

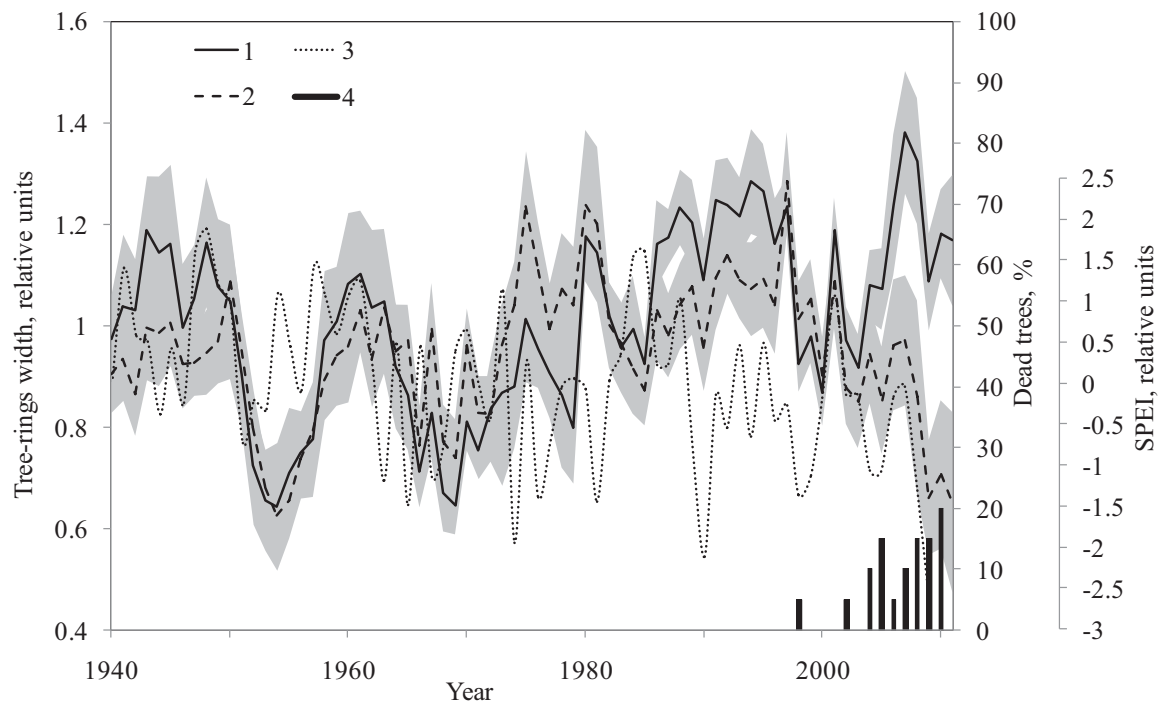
296 No significant correlations were found between radial tree growth and temperature and
 297 precipitation. The relationship between tree radial growth and SPEI index was developed from
 298 correlations over the period from 1940 to 2009 yrs (with window sizes of 3, 5, 7, 9, 11 and 15
 299 yrs). To do this, a correlation was established between the first selected years of the climate
 300 record and the corresponding years for the tree-ring record. The same process was repeated with
 301 a 1-year lag through the end of the SPEI record. Similarly, a coefficient of synchronization was
 302 calculated. Tree radial increment was significantly correlated and synchronized with SPEI
 303 drought index ($r^2 = 0.37$, $r_s = 80$; Fig. 7). Trajectories of “dead” and “survivors” diverged at the
 304 beginning of the 21st century. Tree mortality was observed after the 1998 drought (Fig. 8).



305
 306 Fig. 6. Dead stands area (1, r_1^2) and mortality elevation limit correlations with SPIE (2, r_2^2). r_1^2 and r_2^2 are
 307 significant at $p < 0.02$ and $p < 0.08$, correspondingly.



308
 309 Fig. 7. Running 15-year coefficients of synchronization (1) and correlation (2) between tree ring radial
 310 growth SPIE and. 3 – level on medium (>69%) synchronization, 4 – significance level ($p>0.05$) for correlation
 311 coefficients. Note: synchronization coefficient values $69>r_s>50$ were considered as a low, $r_s>69$ were considered
 312 as a satisfactory (Shiyatov, 1986).



313
 314 Fig. 8. Tree ring chronology of (1) “survivors” and (2) “dead and decline” trees. Confidence
 315 interval ($p<0.05$) shown by grey background. 3 - SPEI dynamics, 4 – percentage of sampled
 316 dead trees ($n=21$) which dying in the given year.

317 4. Discussion

318 Siberian pine mortality was tracked since 2006, when mortality was first detectable (Fig.4a,
319 b). The spatial pattern of dead forest stands was uneven with respect to topographic relief
320 features. Dead stands were mainly located on slopes with southern aspect (Fig. 6b). This pattern
321 is typical for drought-induced mortality (e.g., aspen mortality in the western US (Huang and
322 Anderegg, 2012), or birch mortality in Trans-Baikal area, Russia (Kharuk et al., 2013). The area
323 of dead stands was correlated with a drought increase ($r_1^2 = 0.98$; Fig. 5).

324 The majority of dead stands were located on relatively steep slopes with the median at about
325 13° (Fig. 5c). The slope and aspect of those stands are approximately normal to peak direct solar
326 radiation during the middle of June to the beginning of July (when sun elevation angles reach
327 about 60°). Mortality was relatively higher within convex terrain elements (Fig. 5c), whereas
328 within areas of higher soil moisture (e.g., toeslopes and river alluvium terraces) mortality was
329 lower. These facts suggest moisture stress as a factor of forest mortality. The other evidence of
330 moisture stress impact is a strong correlation between mortality and drought index (Fig. 8).
331 Mortality was maximal within the lower elevation belt (starting from the footslope) and
332 decreased with elevation with no signs of mortality above 900 m (Fig. 4b). This elevational
333 pattern could be attributed to increased precipitation at higher elevations. Within the study area
334 precipitation increased with elevation by about 1.8 mm m⁻¹, which translates into 460 mm more
335 precipitation at 900 m in comparison with 650 m (i.e., where mortality was first observed; Fig.
336 4). As drought increased, mortality extended uphill and reached elevations of 900 m by the year
337 2012 (Fig. 6). The upward shift of mortality was correlated with SPEI values (Fig.5). It is
338 important to note that Siberian pine (which is also known as "tree-of-fog") is a precipitation-
339 sensitive species with optimal precipitation values >1000 mm year⁻¹. At higher elevations (in
340 addition to precipitation increase) frequency of fogs (clouds) also increased. A drought impact
341 on Siberian pine was amplified by shallow well-drained soils especially at convex relief features.
342 Notably, less drought-sensitive birch and aspen trees, which make up about 1-3% of Siberian
343 pine stands, did not exhibit signs of drought impact.

344 Dendrochronology analysis also supported the hypothesis of the primary role of drought
345 stress in Siberian pine stands decline and mortality. Drought increase (Fig. 3b, c) was
346 accompanied by a decrease in radial increment (Fig. 7). Similar observations were reported for
347 aspen growth during drought years (Hogg et al., 2008). Starting at the end of the 20th century
348 trees increment trajectories diverged. The "decline and dead" group showed negative increment
349 trends, whereas "survivors" temporarily increased their growth increment (Fig. 7). The growth
350 release in the surviving trees was likely caused by a decrease in competition with the dying trees
351 since the surviving and declining trees were interspersed within the same stand. With drought

352 increase in the following years (2008-2009) radial increment of “survivors” also decreased
353 (Fig. 7).

354 Synchronization between tree radial growth and SPEI increased after 1960 and became
355 significant by the middle of the 1970s with highest values observed during the last decade (Fig.
356 7). Similarly, correlation between tree radial growth and SPEI was significant in the mid 1990s
357 and beginning of the 21st century and were increased by repeated extreme droughts during the
358 last decades (1998, 2003 and 2012 yrs; Fig. 7). This coincided with observations of other authors
359 of increased growth sensitivity to climate in the years preceding mortality (McDowell et al.,
360 2008). Increased synchrony between tree ring growth and SPEI also suggest that past droughts
361 narrowed the Siberian pine ecological niche. Thus, Siberian pine mortality occurred after
362 exposure to prior droughts (years 1998, 2002) that initiated tree ring growth decline (Fig. 8).
363 Similarly, aspen stands (*Populus tremuloides*) experienced severe stress in the beginning of the
364 21st century, which caused mortality of stands (Worrall et al., 2010; Anderegg, 2012).

365 The progressive decrease of tree increments (Fig. 8) indicated, along with water stress, the
366 presence of other effects (including possibly carbon starvation). Although in recent studies of
367 aspen die-off in western North America no evidence was found that drought stress led to
368 depletion of carbohydrate reserves (Anderegg et al., 2012). A potential (also secondary) role in
369 Siberian pine decline may be bark beetles attack. Thus, insect and larvae galleries were observed
370 within the bark and xylem of severely weakened and dead trees. It is known that bark beetles
371 attacked weak and old growth trees (e.g., Kharuk et al., 2004). However, this was not the case
372 within the study area where stands were not over mature (mean tree age was 160 years) and
373 Siberian pine stands become overmature at Age >300 yr. Evergreen conifer decline and mortality
374 in some Russian forests were also attributed to root fungi impacts, which were facilitated by a
375 drought-caused decrease in stand vigor (Chuprov, 2008; Pavlov et al., 2008). Fungi and insect
376 attacks should be considered as drought co-factors in the DNC decline phenomenon, which
377 agrees with conception of multiple mechanisms of drought-induced mortality (water stress,
378 carbohydrate depletion, and insect, fungi and bacterial attack) (McDowell et al., 2008;
379 McDowell, 2011; Anderegg et al., 2012; Choat et al., 2012; Fetting et al., 2013).

380

381 The problem of Siberian pine decline has a special significance for forest management,
382 because Siberian pine stands logging is strongly prohibited with the exception of declined stands.
383 In the last case, selective cutting is allowed. Thus legitimate forest harvesting is dependent on
384 timely management decisions based on forest monitoring data. Increasing climate impacted
385 Siberian pine mortality during recent decades and expected increase of precipitation-sensitive
386 species mortality point to the need for changes in forest management policy.

The studied site is within the marginal area between the forest-steppe and black taiga area, and further increases in drought impacts may turn this area into forest-steppe. This will lead to, in particular, introducing drought-resistant species (*Pinus silvestris*, *Larix sibirica*) via natural succession. Meanwhile an expected decrease of the Siberian pine population in this area will not require its assisted migration (as in the case of *Pinus albicaulis*; McLane and Aitken, 2012). This species is not highly threatened by climate change because its area is (1) broad (from ca 49°N to 67°N) (2) there is evidence of climate-driven increase of Siberian pine area by its invasion into larch habitat and into the alpine tundra zone (Kharuk et al., 2005, 2009).

Along the BI site, DNC within the Kuznetzky Alatau Mountains region experienced increased drought (and vegetation index, EVI, decrease) during the end of the 20th - beginning of the 21st centuries (Fig.3c). Several sites of tree decline and mortality were reported by local foresters within these mountains and its vicinities (Fig. 1, sites 4).

On a broader scale, the Siberian pine stand mortality observed within the Kuznetzky Alatau Mountains is part of the phenomenon of DNC decline and mortality in Siberia, European Russia and Russian Far East. Forest mortality locations based on literature data and the authors' observations are presented in Fig. 1. Notably all reported areas of DNC decline coincided with the zones of negative SPEI values (i.e., drought increase; Fig. 1). Thus, monitoring of drought severity (SPEI) is likely to be useful as an early warning indicator of climate-related mortality across forests in other areas and regions, especially those composed of drought-sensitive species (*Pinus sibirica*, *Abies sibirica* and *Picea obovata*). The data obtained are one of the first observations of drought-induced decline and mortality of DNC at southern border of boreal forests, and supported deforestation scenario within this zone with increasing aridity. Meanwhile with an increase in aridity drought-resistant conifers (i.e., *Pinus silvestris* and *Larix sibirica*) may replace DNC within its habitat. Drought increase may also slowdown Siberian pine seedlings recruitment within the alpine forest-tundra ecotone at southern border of Siberian forests (Kharuk et al., 2010a, 2010b).

This described phenomenon, along with published data on birch stands die-off in the Trans Baikal zone (Kharuk et al., 2013), coincided with world-wide observations of increased episodes of climate-induced forest decline and mortality (Aitken et al., 2008; Worrall et al., 2010; Anderegg et al., 2012), and supports the hypothesis of wholesale redistribution of trees in the next century (Aitken et al., 2008). Thus, the extent, dynamics and causes of decline and mortality in Siberian "dark needle conifer" forests warrants further investigation

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566 **Figure captions**

567

568 Fig. 1. Location of known forest stands decline and mortality in Siberia. Background: evergreen
 569 conifer map (Bartalev et al., 2011). Color scale: SPEI (Standard Precipitation Evaporation Index)
 570 anomaly (2000-2009 vs 1902-2009.). Sites: 1 – spruce stands in Archangelsk region; 2 – DNC of
 571 Kuznetzky Alatau Mountains (location of this study designated by the red box); 3, 4 – DNC
 572 stands in southern Siberia; 5 – fir and Siberian pine site in southern Baikal area; 6 – birch stands
 573 within Trans-Baikal area (Kharuk et al., 2013); 7 – spruce and fir stands in Russian Far East
 574 (Man'ko et al., 1998).

575

576 Fig.2. Climate variables within “Black Iyus” site. (a), (b) – mean air temperature and
 577 precipitation anomalies, correspondingly (1 – annual; 2 – May-August data); (c) – anomaly of
 578 SPEI drought index; (d) – annual (1) temperature and (2) precipitation. Trends for annual
 579 temperature (a) and SPEI (c) were significant at $p < 0.05$. Data were averaged for a cell size
 580 $0.5^\circ \times 0.5^\circ$.

581

582 Fig.3. EVI and SPEI anomaly for the Kuznetzky Alatau Mountains and BI site. Box indicates
 583 location of the BI study area. (a) – EVI anomaly (2012 vs 2000-2012 mean); (b) – SPEI anomaly
 584 (2000-2009 mean vs 1902-2009 mean); c) – EVI (1) and SPEI (2) dynamics for the BI site. Bars
 585 showd 0.95 confidence level. Trends are significant at $p < 0.007$ (EVI) and at $p < 0.023$ (SPEI).

586

587 Fig.4. (a) Forest mortality map (background: topographic map) and (b) trend of forest mortality
 588 from 2006 to 2012 (1 – dead stands area; 2 – elevation limit of dead stands at given year).

589

590 Fig. 5. Dead stands area ($1, r_1^2$) and mortality elevation limit correlations with SPEI ($2, r_2^2$).
 591 3, 4 – linear regressions of the dead stands area and mortality elevation limit, correspondingly.
 592 r_1^2 and r_2^2 are significant at $p < 0.02$ and $p < 0.08$, respectively.

593

594 Fig.6. Characteristics of forest mortality with respect to relief features. (a) – Mortality
595 dependence on aspect; (b) – mortality distribution with respect to slope steepness (dashed line: a
596 median, thin lines: boundaries of 75% of dead stands area); (c) – mortality distribution on
597 concave/convex relief features; (d) – mortality dependence on elevation.

598
599 Fig.7. Running 15-year coefficients of synchronization (1) and correlation (2) between tree ring
600 radial growth and SPEI; (3) – level of medium (>69%) synchronization; 4 – significance level
601 ($p>0.05$) of correlation coefficients. Note: synchronization coefficient values $69>r_s>50$ were
602 considered as a low, $r_s>69$ were considered as a satisfactory (Shiyatov, 1986).

603
604 Fig.8. Tree ring chronology of (1) “survivors” and (2) “dead and declining” trees. Confidence
605 interval ($p<0.05$) shown by gray background; 3 – SPEI dynamics; 4 – percentage of sampled
606 dead trees ($n=21$) which died in the given year.

607